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Summary

The Southwest Washington littoral drift restoration project is a demonstration project that will restore sand to the littoral cell in southwest Washington. This preliminary restoration demonstration project is part of the U.S. Army Corps of Engineers (Corps) Southwest Washington Littoral Drift Restoration Regional Sediment Management program. The planned demonstration project will place sand on Benson Beach, the public beach north of the North Jetty at the mouth of the Columbia River (MCR), and then move the sand into the offshore littoral zone. One proposal for doing this involves pumping the material from a sump area that would be created on the south side of the jetty to Benson Beach using a cutter suction dredge, also known as a pipeline dredge. If this one-time demonstration project proves feasible and successful, up to a million cubic yards of sediment could be used to replenish the outer coast littoral drift system in successive years by the same process. The primary goal of this study was to assess the potential risk of impacts to Dungeness crab from the proposed demonstration process of using the cutter suction dredge to move sediment from the proposed sump area on one side of the North Jetty to the beach on the other side of the jetty.

Because there are no direct measurements of crab entrainment by pipeline dredge operating outside of the lower Columbia River navigation channel, dredge impacts for the proposed demonstration project were estimated using a modification of the dredge impact model (DIM) of Armstrong et al. (1987). The model estimates adult equivalent loss (AEL) of crab using crab population density from trawl surveys, dredge project information (gear type, season, location, volume), and an entrainment function relating crab population density to entrainment by the dredge. The input used in applying the DIM to the Southwest Washington littoral drift restoration demonstration included the specific dredging scenario provided by the Corps, existing data on crab density in previously proposed sump areas, and a series of entrainment functions. A total of fourteen scenarios were modeled and the outcomes compared with six reference scenarios intended to represent realistic to worst cases.

Dungeness crab entrainment and subsequent loss of recruitment to adult age classes and the crab fishery estimated for the Southwest Washington littoral drift restoration project varied widely (over three orders of magnitude) because of the range of assumptions about initial crab density, dredging scenarios, and entrainment functions. Estimated AEL of crab recruited to age 3 years and up ranged from 57 to 9,373 crab; estimated loss of crab recruited to the fishery (males only) ranged from 20 to 3281 crab. Reference scenario results demonstrated that losses to the fishery are probably less than 2000 crab and more likely less than 1500 crab. Although the comparison to reference scenarios helps put the results in perspective, losses to the crab fishery could still span two orders of magnitude. This uncertainty can only be assessed by direct measurements of crab entrainment during the demonstration project, which is recommended to more accurately evaluate crab losses, not only from the single demonstration event but from cumulative losses from successive restoration efforts.

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1.0 Introduction

1.1 Background

Recognition is mounting that there is a need to replenish sediment in the depleted littoral drift system of the southwest Washington coast. One of the proposed alternatives for accomplishing this replenishment is the Southwest Washington littoral drift restoration (SWLDR) project, a demonstration project that will place sand on Benson Beach, the public beach north of the North Jetty at the mouth of the Columbia River (MCR); the sand is then moved from the beach to the littoral zone by natural processes. One proposal involves pumping the material from a specified sump area to Benson Beach using a cutter suction dredge, also known as a pipeline dredge. The proposed sump will be dredged just south of the North Jetty (Figure 1); to a capacity of approximately 500,000 cubic yards (cy). Once sand has been pumped out of the sump, a trailing suction hopper dredge will then replace material in the sump by using it as a disposal site for river sediment obtained while performing routine maintenance dredging in the federal navigation channel. According to the proposed plan, the hopper dredge will begin disposing material into the sump within one month of the pipeline dredge removing sediment from the sump, and will have it filled by the end of the dredging season. If this one-time demonstration project proves feasible and successful, up to a million cubic yards of sediment could be used to replenish the southwest Washington coast littoral drift system in successive years by the same process. The Corps requested the Marine Sciences Laboratory of the U.S. Department of Energy's Pacific Northwest National Laboratory (PNNL) to examine the issue of potential Dungeness crab entrainment during the SWLDR demonstration project.

1.2 Objectives and Approach

One of the criteria being used to assess the effects of using a sump area and the timing of its use is the potential for detrimental impacts to fish and Dungeness crab (*Cancer magister*) resources. The Dungeness crab fishery is a very important fishery resource in both Washington and Oregon; coastal estuaries contribute significantly to Dungeness crab production (Armstrong et al. 2003). *C. magister* enter and use the lower Columbia River and estuary throughout their life cycle, with different ages of crab using different parts of the estuary at different times of the year (Rooper et al. 2002; McCabe et al. 1986; McCabe and McConnell 1989). The primary goal of this study was to assess the potential risk of impacts to Dungeness crab from the proposed SWLDR process of using the cutter suction dredge to move sediment from the created sump area on one side of the North Jetty to the beach on the other side of the jetty.

Although several recent studies quantified entrainment and loss of Dungeness crab from hopper dredges in the Columbia River (Pearson et al. 2002, 2003, 2005), those studies focused on entrainment during navigation channel maintenance and construction dredging. As such, they did not take into account the specific sump location (outside of the navigation channel), the proposed type of dredge (cutter suction or pipeline dredge rather than hopper dredge), or the dredging scenario (short term dredging of a small area rather than continuous dredging of a large area). Because there are no direct measurements of crab entrainment by pipeline dredge operating outside of the lower Columbia River navigation channel, dredge impacts for the proposed demonstration project were estimated using a modification of the dredge impact model (DIM) of Armstrong et al. (1987). The goal was to obtain a range of possible crab entrainment and loss values by using a range of values for several required model inputs.

The work described in this report focuses on potential impacts from dredge entrainment at the sump area during transfer of material from the sump to the beach by pipeline dredge, but not for disposal of material into the sump by hopper dredge. Related disposal impact studies are currently being conducted, and at their completion will be used to guide estimates about associated impacts to Dungeness crab populations in the project area. These studies are currently planned to address placement of material on a nonrestricted bottom rather than in a sump and it is currently not know what difference in impact there will be between the two disposal methods. The application of the DIM to the SWLDR project is described in Section 2, which details DIM inputs and outputs, the dredging scenarios proposed by the Corps, and the specific data and assumptions used to model a range of scenarios. Section 3 presents and discusses the results of the modeled scenarios. Conclusions and recommendations are provided in Section 4; figures and tables are provided in Section 5; and references are provided in Section 6.

2.0 Methods

2.1 Dredge Impact Model Description

The DIM used to evaluate impacts to Dungeness crab from the proposed SWLDR project is described by Wainwright et al. (1992) as an extension of a model developed by Armstrong et al. (1987). The model estimates adult equivalent loss (AEL) of crab using crab population density from trawl surveys, dredge project information (gear type, season, location, volume), and an entrainment function relating crab population density to entrainment by the dredge (Figure 2). The model was modified by Pearson et al. (2002, 2003, 2005) to incorporate direct measurement of crab entrainment by hopper dredge in the MCR entrainment studies, which is the most statistically robust approach to estimating AEL.

The DIM has seven categories of data input, numbered in Figure 2:

1. Dredging scenario (location, gear, season)
2. Crab population parameters (density, age-size structure, and sex ratios)
3. Entrainment function (relationship between crab abundance, dredged volume, and entrainment)
4. Dredged volume
5. Dredge-related crab mortality (by age class 0+, 1+, 2+, 3+ years)
6. Natural survivorship (probability of survival to age of interest, i.e., Age 2+ and Age 3+ years)
7. Fishery harvest on Age 3+ male crab.

Model outputs are shown in red in Figure 2. The input parameters for crab density are combined with the dredging scenario and related entrainment function to yield a crab entrainment rate (R, crab/cy), which is multiplied by the dredged volume to yield total crab entrained (E, number of crab). The model then incorporates dredge-related and natural mortality on an age-related schedule to estimate the number of crab that would not recruit to the Age 2+ and Age 3+ classes, or adult equivalent loss to Age 2+ and Age 3+ (AEL 2+, AEL 3+). Fishery harvest rate and the sex ratio of AEL 3+ crab are needed to estimate the number of male recruits that were lost to the crab fishery as a result of dredging.

2.2 Model Inputs and Assumptions

The input used in applying the DIM to the SWLDR demonstration included the specific sump dredging scenario provided by the Corps, existing data on crab density in previously proposed sump areas, and a series of entrainment functions. Because there is a lack of site- and dredge-specific data for the pipeline dredging from the proposed sump area, a number of assumptions associated with the input terms were made. The following assumptions were clarified and reviewed by the Corps and resource agencies before running the DIM to estimate potential crab losses from the littoral drift restoration project.

2.2.1 Dredging Scenarios

The proposal for the SWLDR uses a cutter suction (pipeline) dredge to pump up to 500,000 cy of material from the proposed sump area to Benson Beach over approximately 6 weeks in summer, planned for July 15 through August 31. The proposed sump area (Figure 1) is 600 ft by 3000 ft, or 16.7 hectares (ha); its location was selected as being less impacting to the North jetty and is expected to have a lower abundance of crab during the proposed dredging season than would other previously proposed sump areas located slightly to the east, based on trawl surveys conducted in the summer of 2003 (Williams et al. 2004). The total project volume was assumed to be 500,000 cy for the purpose of estimating crab entrainment in the DIM. To model crab losses specific for the demonstration project, a basic dredging unit or single dredging event needed to be defined. The Corps defined the basic dredging unit of the cutter suction dredge as "one full swing of its ladder covering a lateral distance of 300 feet. The dredge will remove about 250 cy in one swing (event). Once the dredge finishes this event, it begins swinging the opposite direction, a few feet forward of the previous swing. Each swing of the ladder correlates to about 0.00836 ha/250 cy removed." The Corps anticipates that the cutter suction dredge will cover the entire sump area of 16.7 ha in a single pass without redredging any area, providing a ratio of dredged area to volume dredged of 0.033 ha per thousand cubic yards (kcy).

For both project-specific and nonspecific dredging scenarios, the dredging season was assumed to be July through August, and the total dredged volume was assumed to be 500 kcy. The SWLDR sump-specific dredging scenario (SS) assumed that the pipeline dredge would make a single pass over the sump area, removing 1 kcy for every 0.033 ha area dredged. The SS scenario was used in DIM runs with a fixed entrainment function (Section 2.2.3). The nonspecific dredging scenario (NS) made no assumption about the relationship between area and volume. This scenario applied to DIM runs using literature-derived entrainment functions (Section 2.2.3).

2.2.2 Crab Population Density

Crab density, age structure, and sex ratios in the proposed dredging area are important input parameters to the DIM. However, there are no existing data for the exact location of the candidate sump area. Existing data are available for nearby previously proposed sump areas (Williams et al. 2004), for the Columbia River Bar and estuary (Emmett and Durkin 1985; McCabe et al. 1986; McCabe and McConnell 1989; and Larson 1993), and for other coastal estuaries (Rooper et al. 2002). Density estimates, age distribution and sex ratios, and gear efficiency uncertainty for the existing data were considered when selecting the SWLDR DIM input data and assumptions.

2.2.2.1 Existing Crab Density Data

A trawl study by Williams et al. (2004) that covered several previously proposed sump areas found that crab density appeared to decline from east to west. Therefore, the present candidate sump area was located west of the 2003 sampled area. The 2003 trawl samples were collected using a 3-m plumb staff beam trawl incorporating a net body composed of 14-mm mesh, a 5.5-mm mesh-lined cod-end, and a double strand of “tickler” chains on the ground rope. The beam holds the effective net opening at a constant width of 2.3 m, as compared with most conventional otter trawls in which the net opening can vary substantially under different conditions. The “tickler chain” on the ground rope increases the capture efficiency of crab and flatfish; tom-weights are used to keep the trawl on the bottom. This gear is the recommended method for sampling nearshore subtidal soft-bottom habitats in Puget Sound and coastal estuaries (Gunderson and Ellis 1986; Armstrong et al. 1987; Gunderson et al. 1990; Miller et al. 1990; Simenstad et al. 1991). However, it has been acknowledged that efficiency may be low for more motile species or particular life history stages, and may also vary over different bottom substrates. To obtain a quantitative crab density, captured crab caught were divided by the area trawled per sample (estimated as the effective beam width of 2.3 m X the trawl length in meters) converted from square meters to hectares.

Crab densities observed in the sump areas over the course of the 2003 study (Figure 3) appear to be within the range of densities reported elsewhere, especially for Age 1+ crab in what has been described as “lower main channel” habitat by Rooper et al. (2002). This study reported mean annual densities of Age 1+ crab in June and August ranging from approximately 200 to 600 crab/ha in Yaquina Bay and Coos Bay, 200 to 1600 crab/ha in Grays Harbor, and 200 to 1200 crab/ha in Willapa Bay, with considerable year-to-year variability. The crab densities reported by Rooper et al. (2002) are relative densities (not adjusted for trawl gear efficiency).

Previous studies of crab distribution within the Columbia River estuary include those of Emmett and Durkin (1985), McCabe et al. (1986), McCabe and McConnell (1989), and Larson (1993). Studies by the National Marine Fisheries Service (McCabe et al. 1986; McCabe and McConnell 1989) described the abundance and size class structure of Dungeness crab in or near frequently dredged areas in the Columbia River estuary from November 1983 through September 1988. The study by McCabe et al. (1986) noted that crab populations associated with the Columbia River Bar were predominantly composed of young-of-the-year (YOY) crab entering the estuary from the ocean, and increased in density during the spring and summer of both years. Interannual abundance varied substantially, from less than 50 YOY crab/ha observed in 1986 to 1988, to greater than 600 YOY crab/ha observed in 1985 (Larson 1993).

Of the six subtidal stations that made up the Columbia River Bar "region" in McCabe et al. (1986), Station 26 was the only sampling location in close proximity to the proposed sump area (Figure 1). Averaged over all years and months, crab abundance was considerably higher at Station 26 than at all other stations in the Bar region, with mean YOY crab densities of greater than 600 crab/ha and older crab (Age 1+ and greater) densities of 40 to 60 crab/ha (Larson 1993). These numbers were corrected for gear efficiency (see below). It should be noted that in the McCabe et al. (1986) study, often Station 26 was not sampled because of the high density of crab pots in this area. McCabe et al. (1986) also noted the considerable variation in crab densities among individual stations in the estuary, and also within specific stations at different times. For example, at Station 26 during the months of July-August 1984, total crab densities did not exceed 50 crab/ha, whereas during the same time period in 1985, they exceeded 500 crab/ha.

2.2.2.2 Crab Density Input to SWLDR DIM

Although data are lacking for the exact location, for the SWLDR DIM we assumed that crab densities in the candidate sump would be similar to those of sump Area 2 sampled in 2003, which is adjacent to and east of the candidate sump (Figure 1). Sump Area 2 is slightly larger than the candidate sump, and is located at a similar distance of about 610 m south of the North Jetty. In addition to its close proximity to the candidate sump, Area 2 bathymetry is in the same range (33 ft to 39 ft below National Geodetic Vertical Datum), and 2003 trawl depths averaged 38.4 ft. Area 2 was sampled twice per month from July 8, 2003, to November 1, 2003.

Of 39 total trawls in Area 2, 20 trawl samples were collected in July and August 2003. Sample dates, trawl area, and crab catch by age and sex are provided in Table 1. Resulting crab density by age class is provided in Table 2. The relative crab density (T rel) is the direct calculation of trawl catch divided by trawl area for each sample. During the proposed dredging months of July and August, relative total crab densities averaged almost 200 crab/ha (Figure 3), with catches composed primarily of Age 1+ (93 crab/ha) and Age 2+ (89 crab/ha) crab (Table 1).

One source of uncertainty when using trawl data to represent the crab population is the crab capture efficiency for the 3-m beam trawl (i.e., the difference between estimated and actual crab density). Again, existing studies were considered when selecting crab density input assumptions for the SWLDR DIM. In a study by Spencer et al. (2005), abundance estimates of juvenile flatfishes and Dungeness crab made with a towed camera sled were compared with those from diver and 1-m beam trawl surveys in Yaquina Bay. Although efficiency estimates of the beam trawl were not made, researchers found that the camera and diver surveys estimated significantly greater numbers of Dungeness crab than did the beam trawl. Spencer et al. (2005) did not note size classes of crab. In a study by McCabe et al. (1986), an 8-m shrimp trawl with 12.7-mm mesh liner was used to collect crab. Because the sampling efficiency of this gear is unknown and is likely to vary with different size classes of crab, previous trawl efficiency factors from otter trawl studies conducted by Stevens and Armstrong (1984) and Gotshall (1978) were used to estimate crab populations and densities. The trawl efficiency factor is the percentage of each age or size class of crab that would be caught in a trawl. During the summer sampling periods, trawl efficiency factors were as follows: 3.3% for size class I (less than 50 mm) crab and 50% efficiency for all other size classes. Based on the lack of comparable efficiency estimates for the 3-m beam trawl, the efficiency factors of Stevens and Armstrong (1984) were applied to Area 2 July-August 2003 trawl data to estimate absolute crab densities for the proposed sump area. These estimated absolute crab densities (T abs) by age class are provided in Table 2 and Figure 3.

Although the Area 2 catch data are not normally distributed, this is often typical for catch data. The simple sample mean $\bar{x}$ of crab density per age class (1) is still an unbiased estimate of the population mean and long run expectation, and was the recommended term for this analysis.

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \qquad (1)$$

The sample variance for T rel and T abs of each age class (n = 20) was the only variance term considered in the SWLDR DIM, as crab density is the only input variable with a sample distribution.

Crab sex ratios and size-age structure by sampling week is shown in Figure 4. The sex ratio of all age classes was generally skewed toward males during each sampling week and over the entire sampling period (160 males, 91 females). However, statistical evaluation showed that there were too few trawl samples and too few individuals per sample in each age class to determine whether the observed sex ratio was significantly different from 1:1. Therefore, a 1:1 sex ratio of males to females for each age class was assumed in the SWLDR DIM.

2.2.3 Entrainment Function

The entrainment function (β) is a means of relating crab abundance and dredged volume. For the SWLDR demonstration, the question is "what is the crab entrainment rate and efficiency of the proposed cutter suction (pipeline) dredge?" The entrainment rate of dredges is likely to be lower than actual crab densities due to crab avoidance, dredge operation procedures, sediment type, and other factors. Previous crab entrainment studies in the Lower Columbia River by Pearson et al. (2002, 2003, 2005) used a statistically rigorous sampling design to directly measure entrainment rates of crab while aboard the hopper dredge *Essayons* and, therefore, did not need to estimate the dredge's efficiency relative to existing estimates of crab density. Dredging studies that rely on measures of crab density from other sources, such as trawl surveys, however, must attempt to develop relationships between these values.

Few studies have quantified entrainment rates for cutter suction dredges. For example, in Archibald and Bocking (1983), crab entrainment and mortality associated with pipeline dredge operations in British Columbia, Canada, were monitored, but entrainment rates were not calculated (4 crab were entrained during monitoring periods that cumulatively equaled 8 hours). In contrast, a study by Stevens (1981) compared the dredging operations of three types of dredges (hopper, pipeline, and clamshell) in Grays

Harbor, Washington, in 1979. Results indicated that the crab entrainment rate was primarily a function of dredge type (suction vs. clamshell); entrainment rates of the pipeline dredge were not significantly different from those of other types of suction dredges (i.e., hopper dredges), but were higher than entrainment rates of the clamshell dredge. For the pipeline dredge, weighted average daily entrainment rates were approximately 0.243 crab/cy. Stevens (1981) also noted that entrainment rate may be affected by sediment type, and that entrainment variability between dredges was more closely correlated with crab densities associated with location and date.

Studies by Armstrong et al. (1987), McGraw et al. (1988), and Wainwright et al. (1992) used a regression relationship to predict hopper dredge entrainment rates using trawl-based density estimates. The relationship was developed in Grays Harbor using entrainment rates measured on the Corps hopper dredge, *Yaquina*, paired with trawls for relative crab density (uncorrected for trawl efficiency) in the same location at the same time. Armstrong et al. (1987) determined that both a linear and a curved relationship would be appropriate to express how dredge entrainment relates to trawl densities. However, the study of Wainwright et al. (1992) suggests that the following linear entrainment function (2) may be more reliable, because the curved function underestimates entrainment rates for density data that have been averaged over space and time:

$$E = a * D \qquad (2)$$

where E is the entrainment rate, crab/kcy, a is the entrainment function coefficient, and D is the estimated crab density, crab/ha.

In terms of the SWLDR DIM, the Wainwright et al. (1992) linear entrainment function is expressed as (3):

$$R * 1000 \text{ cy/kcy} = \beta * T \qquad (3)$$

where R is the entrainment rate in crab/cy, β is the entrainment function coefficient, and T is the crab density in crab/ha.

The final regression model, published in Wainwright et al. (1992), found that the best least squares model yielded an entrainment function coefficient of 0.27, so that crab/kcy = 0.27 * crab/ha for a hopper dredge using relative crab density.

Armstrong et al. (1987) incorporated suggestions by a Crab Study Panel in 1986 that pipeline dredge entrainment be less than 100% of hopper dredge rates due to differences in dredge operation associated with area swept (less per-unit time) and lower efficiency. In considering these features together, it was decided that a more realistic entrainment rate for the pipeline would be 33% of the hopper entrainment rate, yielding an entrainment function coefficient of 0.09 for pipeline dredge entrainment.

Finally, in Larson (1993), unpaired crab trawl data were compiled with dredge entrainment data from similar locations in the Columbia River (1985-1988) (Table 3). In Pearson et al. (2002), these data were reviewed to gain perspective on crab impacts in the Columbia River. It was found that the dredge entrained crab at much higher apparent densities than did the trawl and at different rates by age class (Table 3) (dredge-to-trawl ratio at Age 0+ = 1.75; Age 1+ = 6.73). The authors in Pearson et al. (2002) therefore suggested that the relationship between trawls and dredge entrainment was not the same in the Columbia River as in Grays Harbor, and concluded that it would be inappropriate to apply the entrainment function from Grays Harbor to the Columbia River until and unless paired trawling and entrainment measurements provide site-specific data to validate the function.

In the absence of direct measurements of dredge entrainment for a pipeline dredge operating just south of the Columbia River north jetty and outside of the navigational channel, a series of entrainment functions were used in the SWLDR DIM, in combination with the dredging scenarios and crab densities described above. For most DIM scenarios, dredge entrainment was assumed to be equal to or less than crab density (T rel or T abs). The range of entrainment function coefficient values included both fixed values (i.e., $\beta = 1.0$ for 100% of crab entrained by dredge, $\beta = 0.1$ for 10% of crab entrained by dredge) and literature-derived values (i.e., $\beta = 0.27$ and $\beta = 0.09$ for regression relationships between crab/ha and crab/kcy in hopper and pipeline dredges, respectively). To address the possibilities of higher apparent crab densities in a hopper dredge versus absolute trawl densities and variable entrainment by age class observed by Larson (1993), the DIM was run using the literature-derived age-specific β values of 1.75 for Age 0+ crab and 6.73 for Age 1+ and older. Because dredge entrainment in general is expected to be less than the absolute crab density (as shown in the paired hopper dredge and trawl studies), and pipeline dredge entrainment in particular is expected to be lower than hopper dredge entrainment, these latter entrainment functions are expected to represent a case of extremely high crab entrainment and loss estimates.

2.2.4 Dredge Mortality

Few studies have been conducted on mortality rates for pipeline dredges. The best available data are from a study of crab losses during pipeline dredge disposal in a confined upland site (Stevens 1981), but size-dependent mortality was not considered. The DIM typically takes into account a mortality schedule that varies with age and size, as hopper dredge entrainment studies have shown that smaller crab are more likely to survive dredge entrainment than are larger crab (Armstrong et al. 1987). In the SWLDR DIM application, each dredging scenario and crab density combination was modeled with two different dredge-mortality assumptions. In the absence of size-dependent mortality rates for pipeline dredges, the first assumption involved using the size-dependent rates derived by the Crab Study Panel (1986) that were used by Armstrong (1987). These assumed mortality rates were 10% for Age 0+, 60% for Age 1+, and 86% for crab older than Age 1+. The second dredge-mortality treatment was a worst-case estimate assuming dredge mortality was 100% for all age classes, which could be the case if material from the sump were deposited near the high tide line of Benson Beach, potentially stranding any crab surviving initial entrainment.

2.3 Summary of Modeled Scenarios and Assumptions

In Pearson et al. (2002, 2003, 2005), the DIM of Armstrong and colleagues (Armstrong et al. 1987; Wainwright et al. 1992) was adapted to successfully accept direct measurements of entrainment rates and then to estimate the AEL of Dungeness crab from dredging in the MCR and Lower Columbia River (Figure 2). Although direct measurement of crab entrainment rates remains the most statistically robust approach to estimating AEL, the DIM was modified to accept crab density data from trawls collected in adjacent areas in 2003 under different dredging scenarios to estimate AEL for the SWLDR demonstration project. A series of scenarios and assumptions about input parameters were made, with the goal of encompassing the range of possible loss estimates. Dredging scenarios, input parameters, and assumptions are summarized below; key scenario and input definitions are provided in Table 4. Table 5 relates the input parameters to the model steps, indicating the number of levels (modeled inputs) for each parameter and the source of the input data or basis for an assumption. A summary matrix of the 14 modeled scenarios is provided in Table 6.

Dredging Scenarios: Two types of dredging scenarios were required to incorporate differences in entrainment function values. The SWLDR sump-specific dredging scenario (SS) assumed that the pipeline dredge would make a single pass over the sump area, removing 1 kcy for every 0.033 ha area dredged. The SS scenario was used in DIM runs with a fixed entrainment function (i.e., $\beta = 1.0$, see Section 2.2.3). The nonspecific dredging scenario (NS) makes no assumption about the relationship between area and volume; this scenario was applied to DIM runs using literature-derived entrainment functions (i.e., $\beta = 0.27$, see Section 2.2.3) because this relationship is incorporated in the entrainment function. For both project-specific and nonspecific dredging scenarios, the dredging season was assumed to be July-August and the total dredged volume was assumed to be 500 kcy.

Crab Density (T): All SWLDR DIM runs assume that the candidate sump area is represented by the July-August 2003 crab density estimates for Area 2 of Williams et al. (2004). However, because there is uncertainty associated with the ability of the trawl to capture all crab in its path, a number of DIM runs assumed an absolute trawl density (T abs), incorporating the trawl gear efficiency factors of Stevens and Armstrong (1984). A 1:1 sex ratio of males to females was assumed for all age classes. Crab immigration into the dredged area between dredge events was considered irrelevant, based on the current assumption that the pipeline dredge will cover the entire sump area with an operation that dredges each part of the sump area only once. In the absence of additional information, crab density will be assumed to be constant over the entire sump area during the proposed July-August dredging period.

Entrainment Function: Because there are no existing data on crab density for the specific proposed sump location or on dredge entrainment by the specific type of dredge being used at the location, it follows that there is no readily applicable entrainment function relating the two variables. Therefore, both fixed and literature-derived entrainment functions with coefficients (β) ranging from 0.09 to 6.73 were used in combination with the dredging scenarios and crab densities described above. These functions are defined in Section 3.2.2 and in Table 4.

Mortality and Fishery Harvest Functions: The DIM model input requires both dredge-related mortality and natural mortality (described here as natural survivorship). For all dredging scenarios, crab losses were estimated using both age-related dredge mortality and 100% dredge mortality assumptions. Natural survivorship was assumed to be age-related in all cases, following the survivorship schedules of Armstrong et al. (1987) and Wainwright et al. (1992). Only adult male Dungeness crab are allowed to be harvested from the Columbia River. Although size regulations vary slightly between Washington and Oregon and between commercial and recreational crab fisheries, harvestable male crab are generally Age 3+ and up. To estimate the loss of recruits to the fishery, a harvest rate of 70% of male AEL 3+ crab was assumed in the model, which is consistent with previous applications of the DIM (Armstrong et al. 1987; Wainwright et al. 1992; Pearson et al. 2002, 2003, 2005).

As noted previously, all assumptions are provided in Tables 4 and 5; the range of dredging scenarios, crab density estimates, entrainment functions, and mortality/harvest functions resulted in 14 input scenarios to the DIM (Table 6).

2.4 Evaluation of SWLDR DIM Output

Because the SWLDR DIM approach was intended to yield a range of possible outcomes, it is useful to consider several "reference" cases against which to evaluate the results of the modeled scenarios. The most quantitative crab entrainment data available for the mouth of the Columbia River are those of Pearson et al. (2003). These are direct measurements of crab entrainment by the Corps hopper dredge, *Essayons,* while it was working at the MCR in summer 2002. To provide a comparable reference point for the SWLDR DIM output, the data of Pearson et al. (2003) were filtered to include only MCR samples collected in July and August, and the resulting entrainment rate was projected for a 500 kcy dredged volume. Because this MCR dredging scenario is for a hopper dredge repeatedly sweeping the surface sediment in the dredged area, and a pipeline dredge is proposed for the SWLDR project, the MCR scenario was also adjusted for the 33% pipeline dredge efficiency (relative to hopper dredge) assumed for the other modeled nonspecific dredging scenarios (Tables 4, 6, and 7).

Like the other nonspecific dredging scenarios, the MCR reference scenarios do not consider the small surface area:volume relationship of the proposed SWLDR sump area (Table 4). Nor do the nonspecific scenarios consider that the sump will be dredged in a single pass so that the dredge will not return to an area that has already been dredged. The NS and MCR scenarios assume that the crab density applies to every kcy of the dredge volume, although it is likely that the crabs are not buried more than 2 ft in the substrate. Therefore, two additional sets of reference scenarios were developed that addressed these site-specific concerns while incorporating the most numerically conservative assumptions about crab density and dredge mortality, as follows:

1. A SWLDR sump-specific dredging scenario was employed in which all SS input parameters were retained, but the upper 99% confidence limit of the relative and absolute trawl densities were used as the crab density inputs. The fixed entrainment function $\beta = 1.0$ assumed that all crab in the trawls were entrained by the dredge. Dredge-related mortality was assumed to be 100%. The absolute trawl density input should represent a "very high loss" case against which the modeled average density cases can be evaluated, because the assumption is that crab density is consistently

very high throughout the proposed dredging season. The relative trawl density should represent a "relatively high loss" case, where unadjusted beam trawl crab density is assumed to be higher than 99% of existing July-August trawl densities throughout the proposed dredging season. The sump-specific reference scenarios are referred to as SS ref.

2. A "hybrid" dredging scenario was used in which the dredged volume of a nonspecific dredging scenario was adjusted to account for the site-specific conditions that a) the proposed sump will be dredged in a single pass, and b) that crab are not likely to be evenly distributed throughout the sediment in the sump but would probably reside only in the upper 2 ft of material. Over the 16.7 ha sump area, 2 ft of sediment results in a volume of approximately 135 kcy. This adjusted dredge volume input was modeled with other "high loss" input parameters (T abs, M = 1.0), using both hopper ($\beta = 0.27$) and pipeline ($\beta = 0.09$) dredge entrainment functions for "high" and "expected" loss cases, respectively. The hybrid reference scenarios are referred to as hybrid NS SS ref

The input assumptions for all six reference cases (two MCR, two SS, and two hybrid NS SS) are shown in Table 7.

3.0 Results and Discussion

3.1 Entrainment Rates and Crab Losses for Modeled Scenarios

The SWLDR DIM considered both project-specific and nonspecific dredging scenarios combined with a range of crab population density estimates, dredge entrainment functions, and mortality/harvest assumptions as described in Section 2.3. A total of 14 scenarios were modeled (Table 6). DIM outputs of crab entrainment rates (R, crab/cy), total crab entrainment (E, number crab), adult equivalent loss to Age 2+ (AEL 2+, number crab), adult equivalent loss to Age 3+ (AEL 3+, number crab), and loss of male recruits to the fishery (LRTF, number crab) for the range of modeled scenarios are presented in Table 8. Total entrainment and loss estimates were highly variable, each spanning three orders of magnitude (Table 8). LRTF estimates in particular ranged from a low of 20 crab (SS scenario with $\beta = 0.1$) to a high of just over 3000 crab (NS scenario, age-related $\beta = 1.75$ for YOY crab and $\beta = 6.73$ for Age 1+ and older crab).

The lowest estimates of crab losses occurred when assuming 10% entrainment ($\beta = 0.1$) of crab for the SS dredging scenario, using the lowest average crab density estimate, T rel (Figure 5, Figure 6). Even when the higher, T abs density estimate was used, AEL 3+ and LRTF crab losses were still estimated to be fewer than 100 individuals. Assuming 100% entrainment ($\beta = 1.0$) for the SS scenario was intended to yield a set of "reasonably expected" crab entrainment and loss figures, as these inputs most closely reflect the sump crab density and proposed dredging process. When $\beta = 1.0$ for the SS scenario, AEL 3+ estimates ranged from 566 to 1423 crab, and LRTF estimates ranged from about 200 to 500 crab. The higher estimates result from assuming absolute trawl density and 100% dredge-related mortality. The greatest uncertainties in the SS scenarios reside in the actual proportion of crab present in the dredging area that would be entrained.

The nonspecific dredging scenarios generally yielded higher estimates of crab entrainment and adult losses and associated higher error (Table 8, Figures 7 and 8). Total entrainment, adult losses, and loss to fishery estimates were highest for the hopper dredge scenario using the entrainment functions of Larson (1993). This was expected because that scenario not only used the trawl efficiency-corrected absolute crab density (T abs), it also assumed that dredge entrainment was much greater than the assumed crab density. Both of these assumptions magnified the number of juvenile (YOY and Age 1+) crab contributing to loss estimates for this scenario relative to any other dredging scenario. For one thing, T abs for YOY is about 30 times greater than T rel, and with $\beta = 1.75$ for YOY crab, the number of YOY crab entrained was much higher than for any other scenario. Secondly, while T abs for Age 1+ is only twice T rel, Age 1+ crab dominated the Area 2 trawls, and with $\beta = 6.73$ for Age 1+ crab, the estimated number of Age 1+ crab entrained was also much higher than for any other scenario. Even though natural survivorship of juvenile crab to Age 2+ is very low (Armstrong et al. 1987), the sheer number of juveniles estimated to be entrained drive the adult losses in this scenario. Estimated losses from the NS hopper dredging scenarios using the entrainment function of Wainwright et al. (1992) were about 60% of losses estimated using the Larson (1993) entrainment functions, but were still in the same order of magnitude (e.g., LRTF 1620 to 1983 crab versus LRTF 2667 to 3281 crab) (Table 8). Assuming that a pipeline dredge would entrain 33% of the crab entrained by a hopper dredge resulted in estimated an AEL 3+ of 1500 to 1900 crab (depending on dredge mortality assumption) and an LRTF of 540 to 661 crab.

In all scenarios, the 100% dredge morality assumption increased the overall loss estimates by 23% on average over the age-related dredge morality assumption. This assumption did not influence the range of outcomes as much as the initial dredging scenario, crab density, and entrainment function assumptions. It should also be noted that the variance of T rel or T abs is the only error term considered in the SWLDR DIM, and thus does not reflect the uncertainty associated with scenario selection or entrainment function. The consistent coefficient of variation (0.64 to 0.67) for all cases is derived from the fact that the same basic crab density data input (Area 2 July-August trawls) was used in all modeled scenarios.

3.2 Comparison of Modeled and Reference Scenarios

DIM outputs were evaluated against the set of six reference scenarios as described in Section 2.4 and Table 7. Briefly, the reference scenarios were as follows:

- Directly measured MCR 2002 July-August dredge entrainment, projected for 500 kcy (approximately one third of total MCR dredged volume)
- MCR 2002 July-August entrainment, projected for 500 kcy AND adjusted for 33% pipeline dredge entrainment efficiency relative to hopper
- SS scenario with very high estimator of crab density (99% upper confidence limit of T abs) and dredge-related mortality (M = 1)
- SS scenario with high estimator of crab density (99% upper confidence limit of T rel, M = 1)

- Hybrid NS SS dredging scenario with dredged volume adjusted to account for single-pass dredging event of the proposed sump area; crab distribution assumed to be only in upper 2 ft of 16.7-ha sump area, or 135 kcy dredged volume, $\beta = 0.27$ (T rel, M = 1)
- Hybrid NS SS pipeline dredging scenario with dredged volume adjusted to account for single-pass dredging event of the proposed sump area, 135 kcy dredged volume as above, AND adjusted for 33% pipeline dredge entrainment efficiency relative to hopper, $\beta = 0.09$ (T rel, M = 1)

Table 9 lists the DIM outputs for the reference scenarios; estimated crab losses for the reference scenarios are shown in Figure 9. The MCR crab entrainment analyses of Pearson et al. (2002, 2003, 2005) considered only age-related dredge mortality; this was not changed for the MCR reference scenarios. As noted above, the difference in mortality assumptions was not as influential as other assumptions in the SWLDR DIM. Although crab density is known to vary widely by age and season in the MCR, the direct measurements of crab entrainment in the MCR by Pearson et al. (2002, 2003, 2005) cover the entire MCR area for nearly an entire dredging season (June through October), and are considered to be very robust. Pearson et al. (2003) estimated that 10,471 crab would be lost to the fishery in the course of dredging 4.6 million cy of material from the MCR in 2002; this estimate was projected to an average annual LRTF of about 10,000 crab in an average annual volume of 4.4 million cy. Because the MCR estimates are for a hopper dredge continuously sweeping the upper few feet of sediment, it is not unreasonable to assume that losses in 0.5 million cy (500 kcy) dredged by pipeline dredge from a relatively small nearby area (i.e., proposed sump) would be less than the estimated 1100 crab obtained in the reference scenario in which directly measured entrainment for July and August in MCR was projected for the proposed sump volume. Potentially higher crab density outside of the navigational channel could be offset by the expected lower entrainment rate of a pipeline dredge. Applying the assumed 33% pipeline dredge efficiency adjustment to the MCR 500 kcy scenario yielded a LRTF estimate of 361 crab. Although not nearly as robust as the MCR estimates (note associated standard errors), the other reference scenarios yielded surprisingly similar ranges of LRTF, even though total entrainment was generally lower (Table 9).

Crab entrainment and loss estimates for both modeled and reference scenarios are presented in order of descending AEL and LRTF in Table 10. It is clear from this comparison that the modeled scenarios provided a larger range of possible crab-loss estimates than did the reference scenarios. The range of modeled outputs can be divided roughly into three categories: probable overestimates, probable underestimates, and a range of "reasonable" estimates.

Crab entrainment and losses for the NS scenarios are likely overestimates for the sump area for two reasons: 1) the entrainment function coefficients were developed using hopper dredge data, and hopper dredges are likely to entrain more crab than pipeline dredges primarily because they cover more ground in less time, and 2) the NS scenarios make no assumption about the relationship of dredged *area* to dredged *volume* and, as such, assume that the crab are distributed throughout the entire dredged volume at the assumed density. The NS pipeline dredge scenarios address the relative entrainment-efficiency issue, but not the crab-density distribution issue. The hybrid NS SS reference scenarios attempt to address both of these issues by assuming that the crab are distributed only in the upper 2 ft of sediment rather than throughout the entire dredged volume (Section 2.4).

Crab entrainment and losses are more likely to be underestimated when dredge entrainment is assumed to be less than 20% to 30% of the crab density compounded with a scenario that already assumes a single pass of a pipeline dredge over a relatively small dredged surface area (e.g., SS or hybrid NS SS pipeline scenarios). This was only modeled for SS using $\beta = 0.1$ (Table 10).

The estimates for SS using $\beta = 1.0$ are considered to be in the range of reasonable crab-loss estimates because these DIM assumptions include those most directly related to the proposed dredging scenario. The LRTF for SS, $\beta = 1.0$ ranged from 200 to 500 crab, depending on initial crab density and dredge-related mortality assumptions (Tables 8 and 10). Nonspecific dredging scenarios that took into account the proposed pipeline dredging equipment for the sump also resulted in more "reasonable" estimates of crab entrainment and loss (e.g., NS pipeline).

3.3 Remaining Uncertainty

The SWLDR DIM incorporates many assumptions, but the associated error reported with each entrainment or loss estimate is derived solely from the variance on the Area 2 trawl density input. Thus, assumptions related to crab density are most likely to influence the precision of the LRTF outcome. Actual crab density is known to be highly variable both seasonally and annually; crab behavior could be affected by other factors that could result in attraction to or avoidance of the project area (e.g., disturbance from dredging or fishing, sediment disposal in the sump, or natural factors such as bottom currents, salinity, and suspended sediment loads). Even though the crab density data used in the model (July-August trawls in nearby Area 2, from Williams et al. 2004) compared very well with prior crab density for the Columbia River bar and estuary (Section 2.2), they are not for the exact location of the candidate sump area. Even though Williams et al. (2004) used the recommended methods for sampling nearshore subtidal soft-bottom habitats, actual trawl catch efficiencies are unknown. Other sources of uncertainty are the relatively low number of trawl samples (20) and low numbers of crab in each sample, which increases the uncertainty about the population age and size structure (which is then assumed to be constant for the dredging season) and precludes estimation of a sex ratio other than 1:1. These population uncertainties are compounded when the relative crab densities are adjusted for trawl gear efficiency to absolute crab densities.

The other assumptions to the DIM do not have associated variance estimators; their influence is observed in the range of values used (Tables 4 and 5, Section 2.2). Along with representativeness of the crab density data, another major source of uncertainty is the entrainment factor, or relationship of crab density to dredge entrainment. There is little technical basis for choosing fixed entrainment factors other than perhaps 1.0, which assumes 100% of crab are entrained; fixed entrainment factors tend to magnify the consequence of the crab population inputs. There are a number of reasons why the literature-derived entrainment factors used in the DIM are uncertain. The 0.27 and 0.09 entrainment function coefficients were a) developed using data from other areas (e.g., Grays Harbor), and b) modified for a dredge type that might not accurately represent a dredging scenario. The entrainment function coefficients >1 of Larson

(1993) used data for the Columbia River, but dredge and trawl samples were not paired. There is also uncertainty associated with estimating the dredged area and with trawl gear efficiency. In addition, the entrainment function coefficients >1 were derived from May and June data rather than from July and August, because far fewer data were available for the later months. Because crab densities, particularly YOY, were observed to be higher in spring (McCabe 1986) in the Columbia River bar and estuary, the modeled age-dependent β values could result in overestimates of overall entrainment and loss. Indeed, the estimated total entrainment using these functions was 51,432 crab, which substantially exceeded the total entrainment projected for 500 kcy in the MCR in July and August (30,713 crab, Table 9).

In the absence of direct measurements of Dungeness crab entrainment for the proposed SWLDR demonstration dredging scenario, crab entrainment and loss rates were estimated using the DIM of Armstrong et al. (1987) and Wainwright et al. (1992), as modified by Pearson et al. (2002, 2003, 2005). DIM outputs of total crab entrainment, AEL 2+, AEL 3+, and LRTF for the range of modeled inputs was highly variable, each spanning three orders of magnitude. The degree of uncertainty associated with many assumptions is not quantified, adding to the overall uncertainty associated with the modeled estimates. It is *possible* that any or all of the assumptions for the modeled scenarios are valid and that "true" crab entrainment and losses could occur anywhere in the modeled range (i.e., up to approximately 5000 crab). Despite the many uncertainties remaining, the modeled and reference scenarios begin to provide a sense of the range of "probable" crab entrainment and loss from the SWLDR demonstration project.

4.0 Conclusions and Recommendations

Dungeness crab entrainment and subsequent loss of recruitment to adult age classes and the crab fishery estimated for the southwest Washington littoral drift restoration SWLDR demonstration project varied widely because of the range of assumptions about initial crab density, dredging scenarios, and entrainment functions. Crab losses estimated by the DIM for the SWLDR ranged over three orders of magnitude in each loss category:

- AEL 2+: 126 to 20,829 crab
- AEL 3+: 57 to 9,373 crab
- LRTF: 20 to 3281 crab

As noted in the previous section, despite the many uncertainties remaining, the comparison of modeled and reference scenarios provide a sense of the range of "probable" crab entrainment and loss from the SWLDR demonstration project. Figure 10, a bar graph showing the frequency of LRTF estimates for both modeled and reference scenarios, illustrates that LRTF would probably be less than 2000 crab, and more likely less than 1500, for the SWLDR project scenario. Although the comparison to reference scenarios helps put the results in perspective, the range of estimated losses to the crab fishery still spans two orders of magnitude. This degree of uncertainty may not be acceptable when considering the future impacts of continuing littoral drift restoration if the SWLDR demonstration project proves successful.

Crab entrainment has not been measured on a cutter suction dredge operating at the mouth of the Columbia River; the large range of modeled estimates obtained during this study illustrate that direct measurement of crab entrainment rates remains the most statistically robust approach to estimating AEL and LRTF. The proposed SWLDR demonstration is the first opportunity to obtain site- and dredge-specific measures of Dungeness crab entrainment for what is a promising process for future drift replenishment. Direct measurements of crab entrainment during the demonstration are recommended to more accurately estimate single-event and cumulative crab losses as a result of sediment rehandling at the proposed sump area.

5.0 Figures and Tables

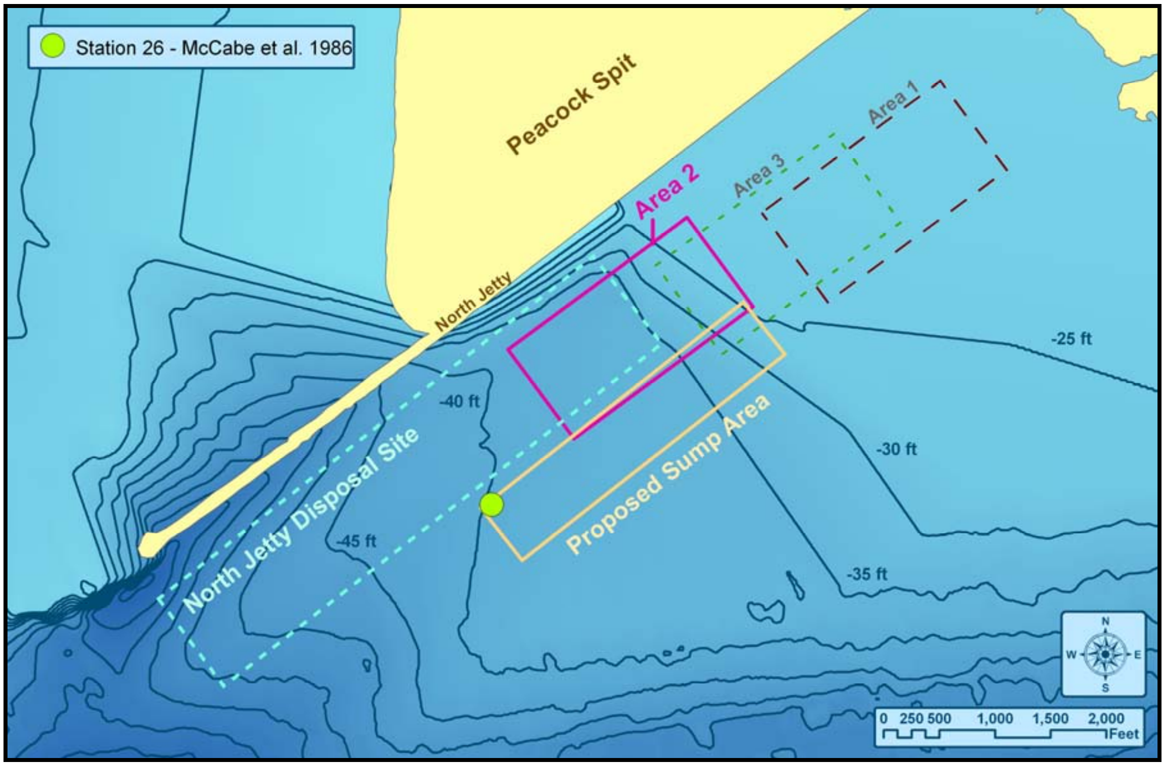

Figure 1. Locations of Proposed Sump Area for Southwest Washington Littoral Drift Restoration Demonstration Project and Sump Area 2 Crab Density Data

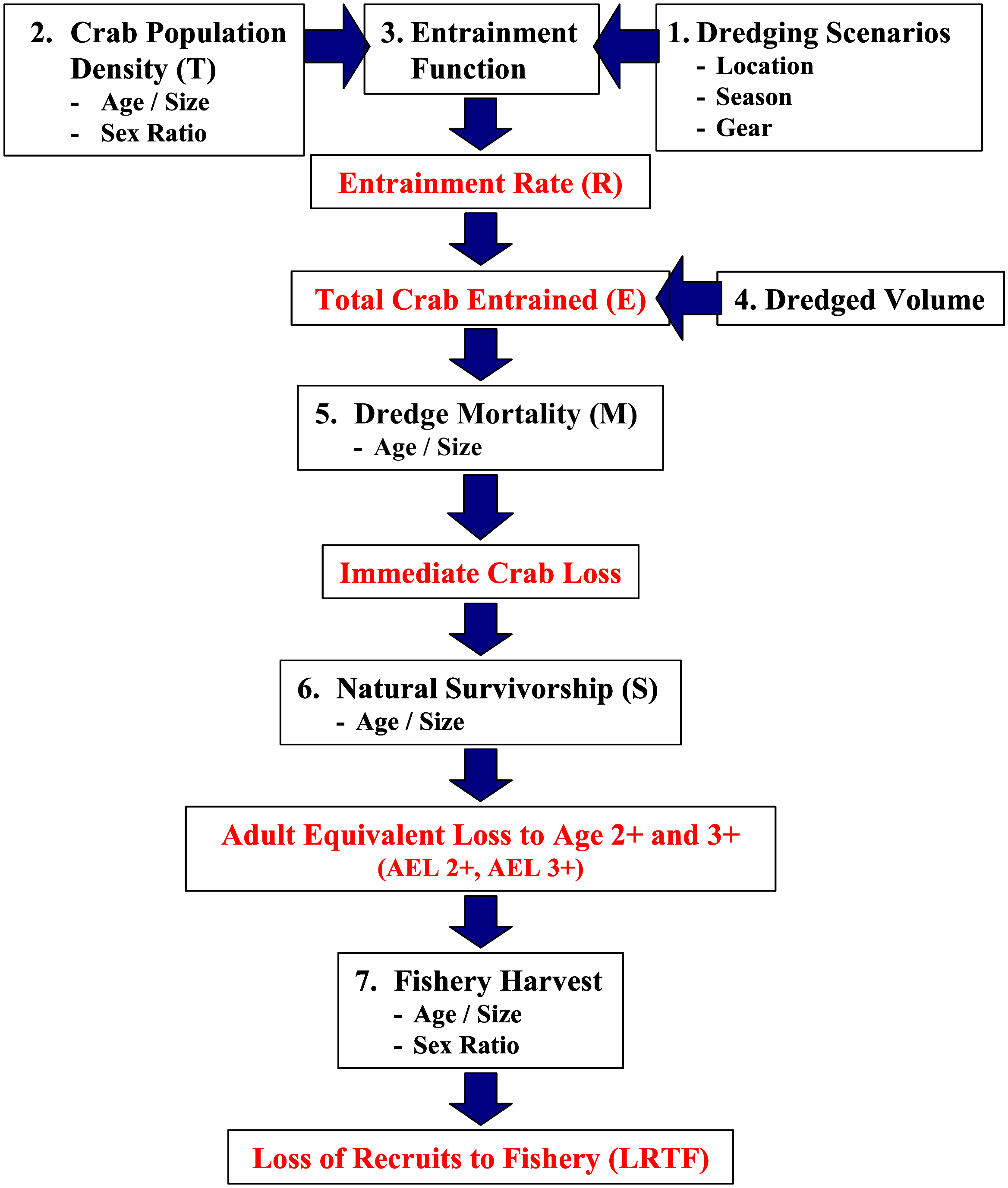

Figure 2. Dredge Impact Model (modified from Wainwright et al. 1992); red indicates model output

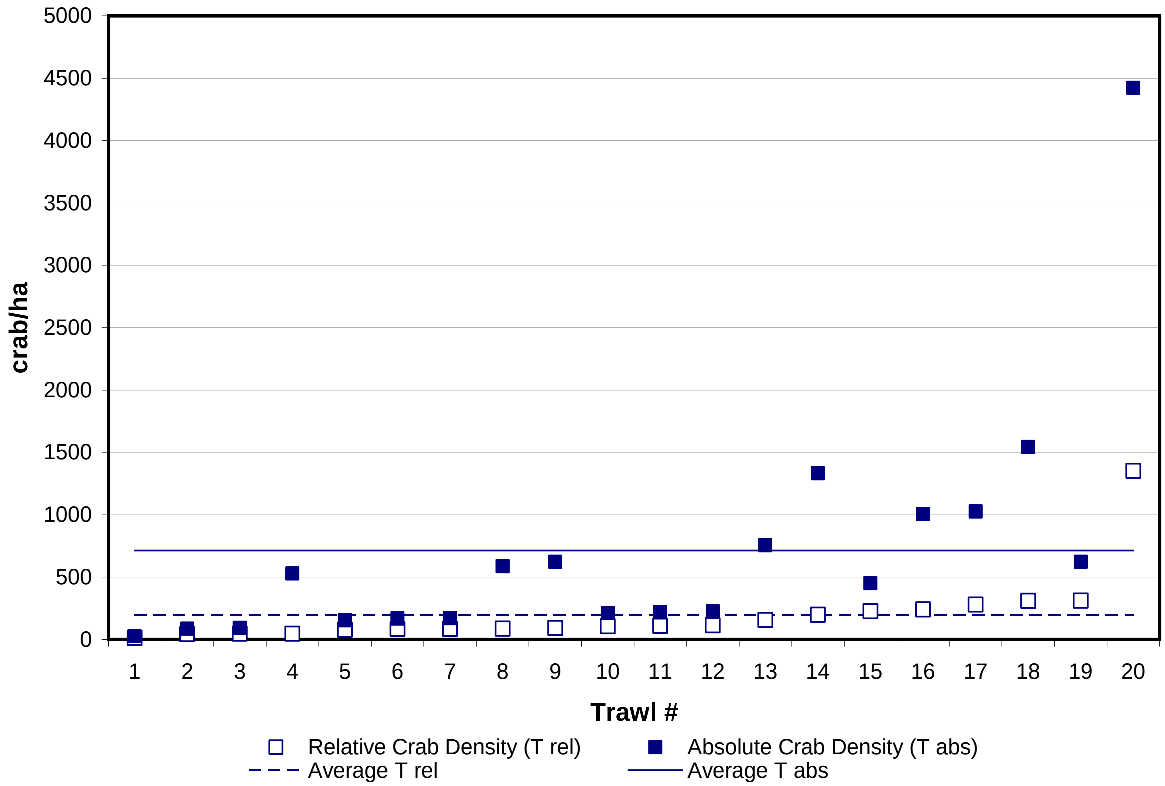

Figure 3. Relative and Absolute Densities of Crab in Trawl Samples Collected at Sump Area 2 in July-August 2003 (data from Williams et al. 2004)

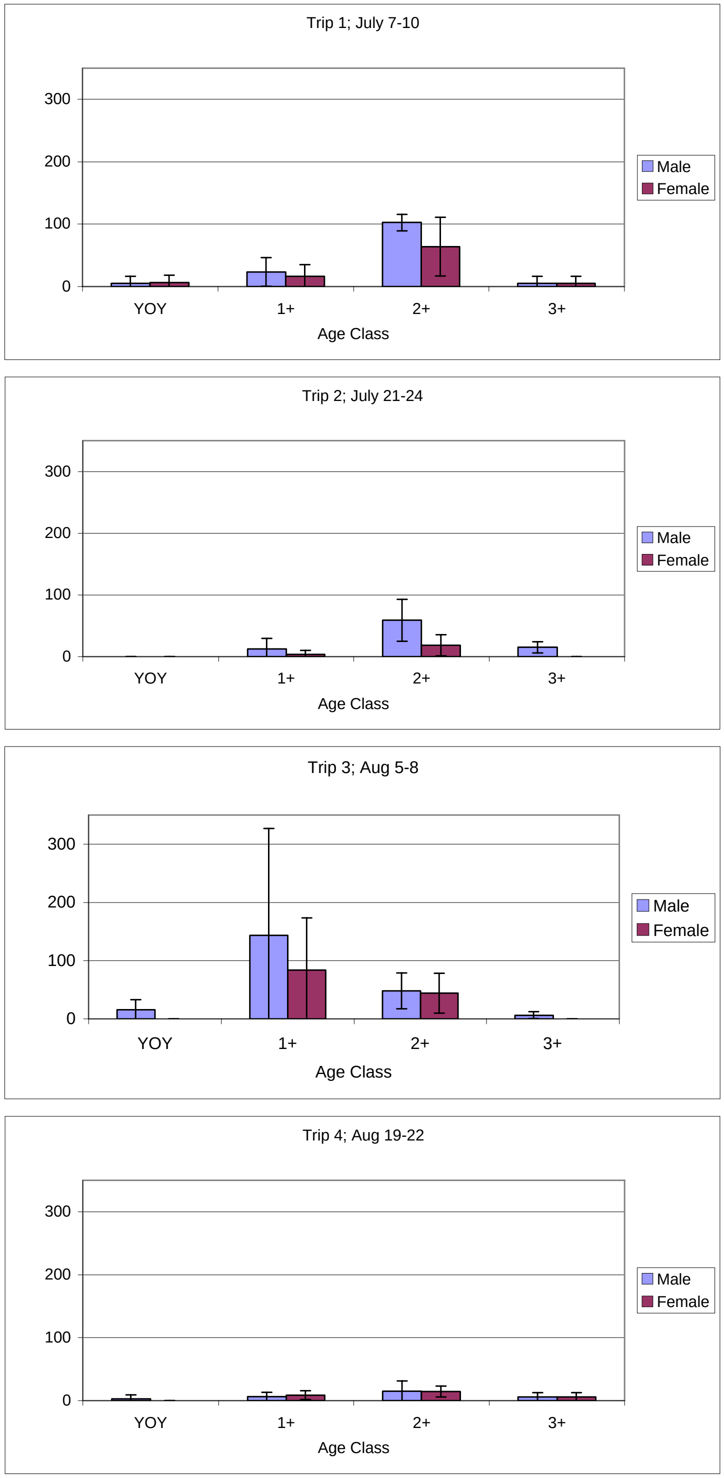

Figure 4. July-August 2003 Sump Area 2 Relative Trawl Density in Crab/ha by Age Class and Sex for Each Sampling Event (±95% confidence interval; data from Williams et al. 2003)

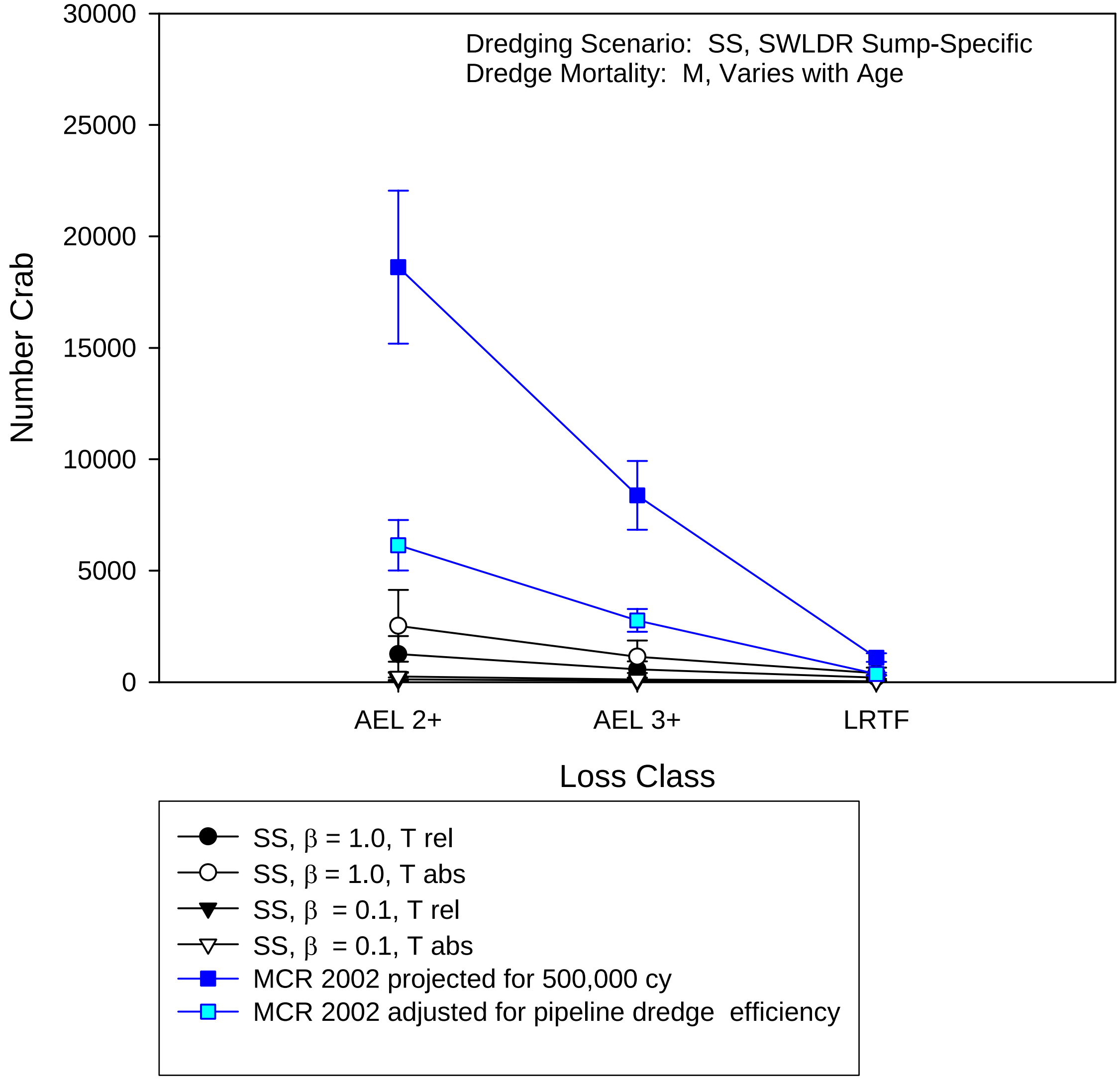

Figure 5. Estimated Crab Losses Resulting from the Sump Area Specific (SS) Dredging Scenario with Fixed Entrainment Function Coefficients of 1.0 and 0.1, Assuming Dredge-Related Crab Mortality Varies with Age

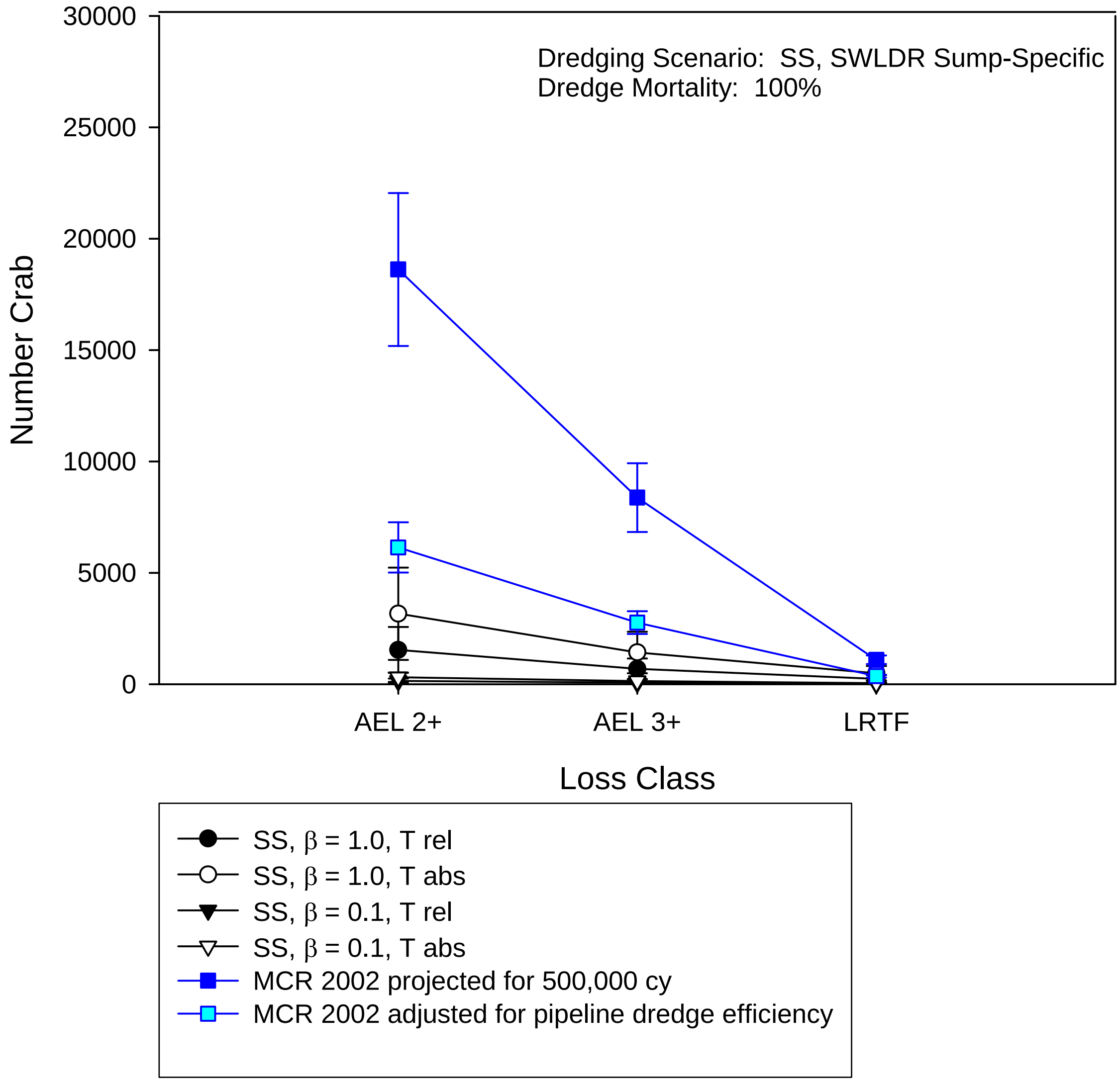

Figure 6. Estimated Crab Losses Resulting from the Sump Area Specific (SS) Dredging Scenario with Fixed Entrainment Function Coefficients of 1.0 and 0.1, Assuming Dredge-Related Crab Mortality of 100%

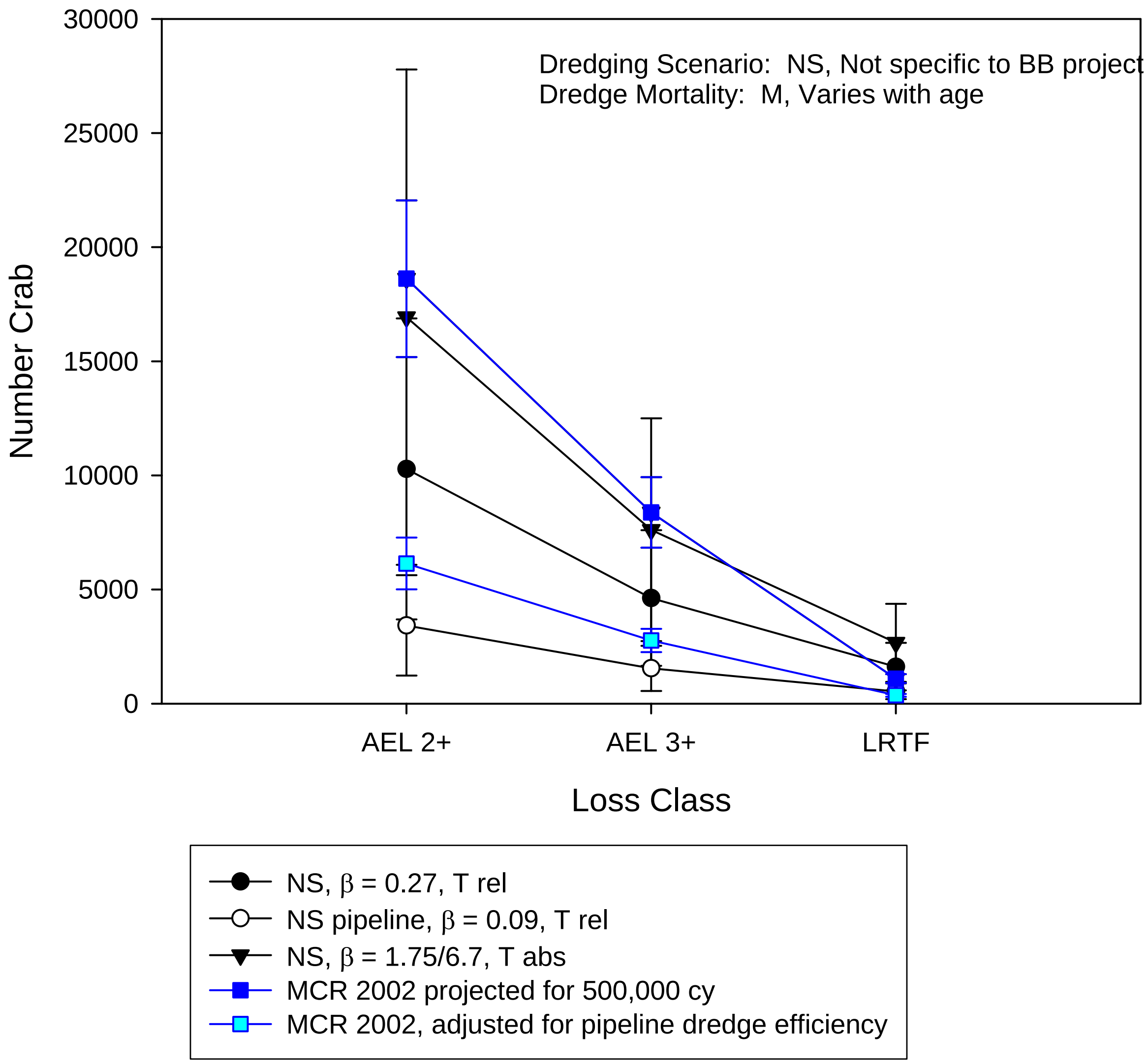

Figure 7. Estimated Crab Losses Resulting from Nonspecific Dredging Scenarios with a Series of Entrainment Functions, Assuming Dredge-Related Mortality Varies with Age

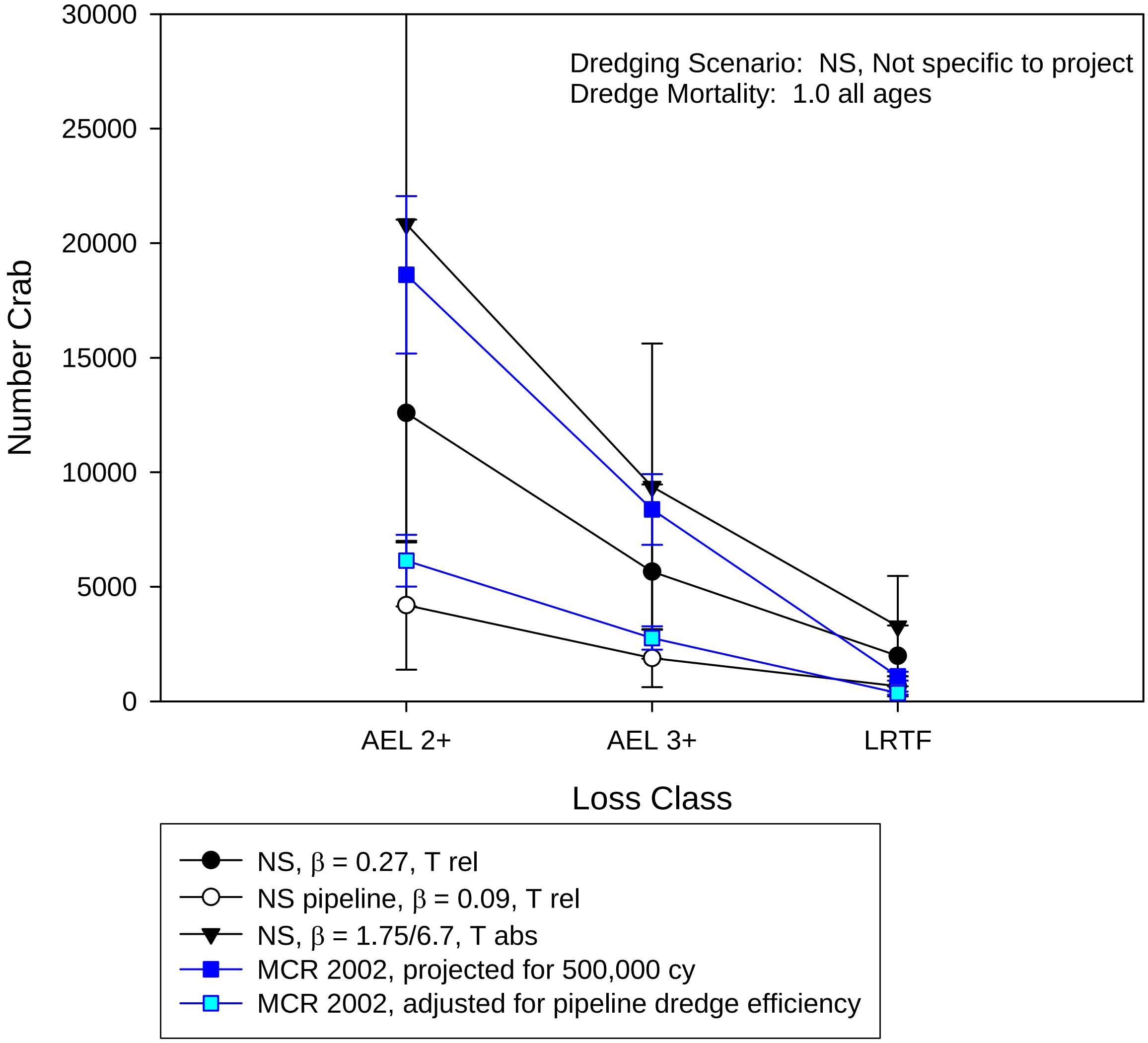

Figure 8. Estimated Crab Losses Resulting from Nonspecific Dredging Scenarios with a Series of Entrainment Functions, Assuming Dredge-Related Mortality of 100%

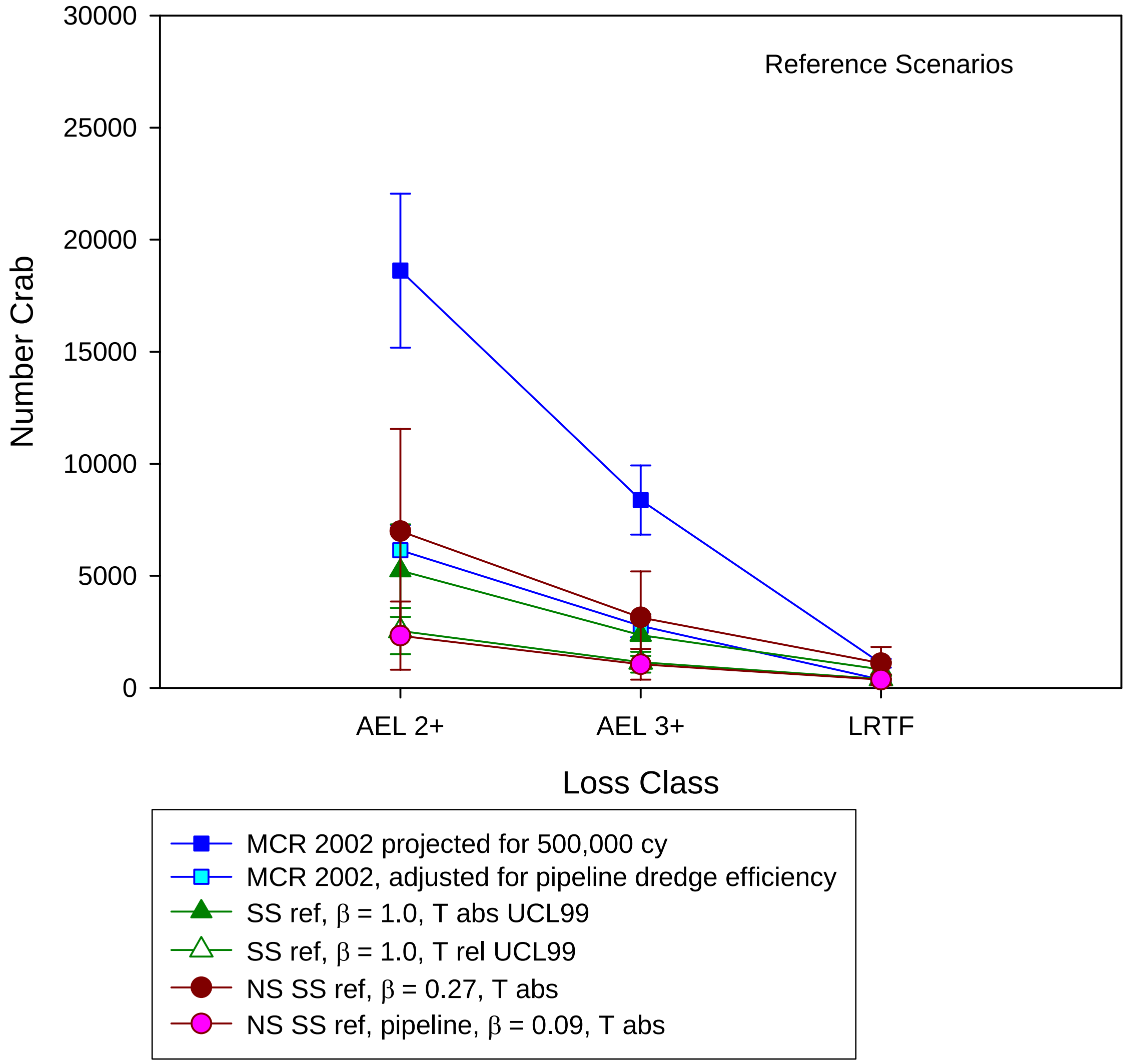

Figure 9. Estimated Crab Losses for all Reference Scenarios

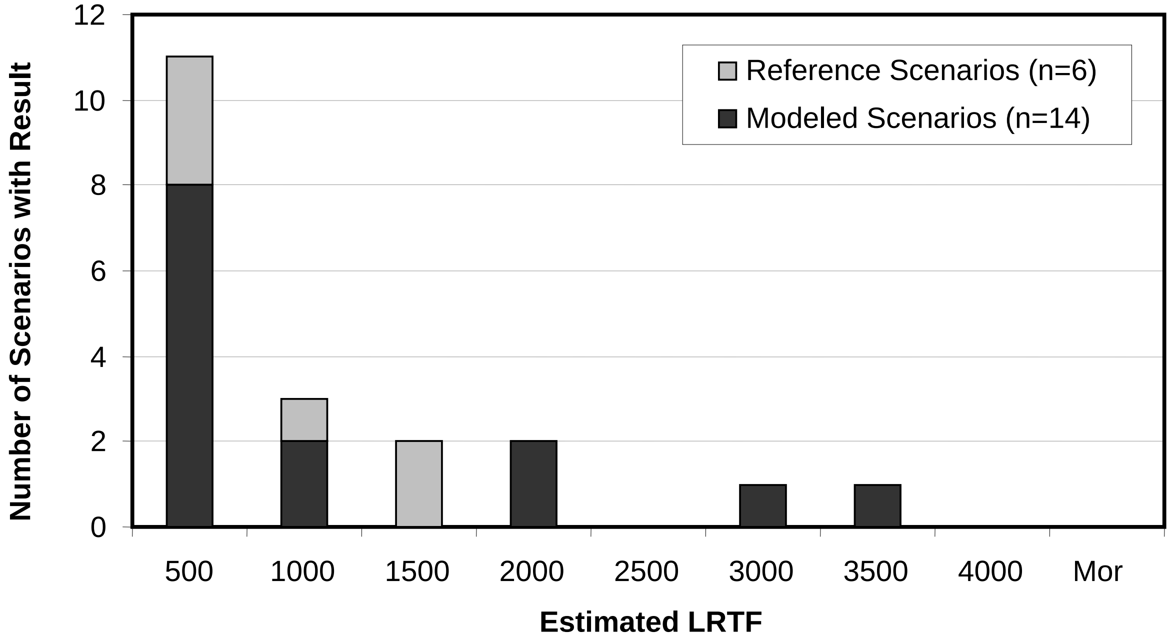

Figure 10. Frequency of Projected Loss of Male Recruits to Crab Fishery For Modeled and Reference Scenarios

Table 1. July and August 2003 Trawl Count Data for Sump Area 2 (from Williams et al. 2004)

Trawl Date	Trawl Area (m2)	Uniden-tified YOY	Male Crab					Female Crab					Total Crab
			YOY[a]	1+	2+	3+		YOY	1+	2+	3+		
			0-50 mm	51-100 mm	101-150 mm	>150 mm	Total Males	0-50 mm	51-100 mm	101-150 mm	>150 mm	Total Females	
7/9/2003	606.83	0	1	2	7	0	10	0	2	5	0	7	**17**
7/10/2003	540.36	0	0	2	5	0	7	1	0	5	0	6	**13**
7/10/2003	605.09	2	0	0	6	1	7	0	1	1	1	3	**12**
7/22/2003	595.34	0	0	0	3	1	4	0	1	0	0	1	**5**
7/23/2003	754.58	0	0	0	0	1	1	0	0	0	0	0	**1**
7/24/2003	658.27	0	0	0	5	1	6	0	0	1	0	1	**7**
7/24/2003	663.71	0	0	3	7	2	12	0	0	3	0	3	**15**
7/24/2003	641.81	0	0	1	4	0	5	0	0	2	0	2	**7**
8/6/2003	685.36	1	0	1	3	0	4	0	0	1	0	1	**6**
8/6/2003	658.62	0	4	45	9	1	59	0	22	8	0	30	**89**
8/7/2003	613.40	0	2	5	3	0	10	0	9	0	0	9	**19**
8/7/2003	674.33	0	0	13	1	1	15	0	4	2	0	6	**21**
8/8/2003	639.93	1	0	0	2	1	3	0	1	5	0	6	**10**
8/8/2003	646.94	0	1	1	3	0	5	0	1	0	0	1	**6**
8/8/2003	617.97	0	0	1	1	0	2	0	1	4	0	5	**7**
8/20/2003	647.41	0	0	1	3	0	4	0	0	0	1	1	**5**
8/20/2003	647.60	0	1	0	0	0	1	0	1	1	0	2	**3**
8/22/2003	692.89	0	0	0	1	0	1	0	1	1	0	2	**3**
8/22/2003	708.01	0	0	0	1	1	2	0	1	2	1	4	**6**
8/22/2003	652.36	0	0	1	0	1	2	0	0	1	0	1	**3**
Total All Dates	**12950.81**	**4**	**9**	**76**	**64**	**11**	**160**	**1**	**45**	**42**	**3**	**91**	**255**

a. YOY Young of year, or 0+.

Table 2. Relative and Absolute Trawl Densities Used in Southwest Washington Dredge Impact Model

Trawl Date	Trawl Area (m^2)	Total Crab	Relative Density[a] (T rel, crab/ha)				Absolute Density[b] (T abs, crab/ha)			
			YOY[c]	1+	2+	3+	YOY	1+	2+	3+
			0-50 mm	51-100 mm	101-150 mm	>150 mm	0-50 mm	51-100 mm	101-150 mm	>150 mm
7/09/2003	606.83	17	16	66	198	0	499	132	395	0
7/10/2003	540.36	13	19	37	185	0	561	74	370	0
7/10/2003	605.09	12	33	17	116	33	1002	33	231	66
7/22/2003	595.34	5	0	17	50	17	0	34	101	34
7/23/2003	754.58	1	0	0	0	13	0	0	0	27
7/24/2003	658.27	7	0	0	91	15	0	0	182	30
7/24/2003	663.71	15	0	45	151	30	0	90	301	60
7/24/2003	641.81	7	0	16	93	0	0	31	187	0
8/06/2003	685.36	6	15	15	58	0	442	29	117	0
8/06/2003	658.62	89	61	1017	258	15	1840	2035	516	30
8/07/2003	613.40	19	33	228	49	0	988	456	98	0
8/07/2003	674.33	21	0	252	44	15	0	504	89	30
8/08/2003	639.93	10	16	16	109	16	474	31	219	31
8/08/2003	646.94	6	15	31	46	0	468	62	93	0
8/08/2003	617.97	7	0	32	81	0	0	65	162	0
8/20/2003	647.41	5	0	15	46	15	0	31	93	31
8/20/2003	647.60	3	15	15	15	0	468	31	31	0
8/22/2003	692.89	3	0	14	29	0	0	29	58	0
8/22/2003	708.01	6	0	14	42	28	0	28	85	56
8/22/2003	652.36	3	0	15	15	15	0	31	31	31
Total All Dates	12950.81	255	222	1863	1679	213	6742	3726	3358	426
Range		1-89	0-61	0-1017	0-258	0-33	0-1840	0-2035	0-516	0-66
Average		13	**11**	**93**	**84**	**11**	**337**	**186**	**168**	**21**
Variance		354	259	52058	4651	126	237660	208233	18604	502

a. Relative density calculated from actual beam trawl data and trawl area from Williams et al. 2004 (Table 1).
b. Absolute density is relative density adjusted for trawl gear efficiency of 3.3% for YOY and 50% for all other age classes during summer sampling periods (from Stevens and Armstrong 1984).
c. YOY Young of year, or 0+.

Table 3. Crab Density Estimated from Unpaired Trawl Catch and Dredge Entrainment Observations in the Columbia River (from Larson 1993)

	0+ Crab Density (crab/ha)		1+ Crab Density (crab/ha)	
Date	**Trawl**	**Dredge**	**Trawl**	**Dredge**
May 1985	333	15,831	13	118
May 1986	0	3,004	31	210
May 1987	1,636	25,764	37	288
May 1988	1,758	No Data	32	No Data
June 1985	56,848	35,943	7	70
June 1986	424	3,849	71	183
June 1987	576	8,527	14	295
June 1988	303	1,822	9	96
Mean	7,735	13,541	27	180
Dredge:Trawl Ratio		**1.751**		**6.729**

Table 4. Definitions of Input Parameters Used in the SWLDR Dredge Impact Model

Input Parameter	Abbreviation	Definition
Dredging Scenarios	SS	Scenario is specific to SWLDR demonstration project, assuming a single pass over sump area with surface area:volume relationship of 0.033 ha/kcy (from dredging unit of 1 sweep of pipeline dredge = 250 cy in area 3 ft X 300 ft = 900 ft^2 or 0.00836 ha per 250 cy. 4 X (0.00836 ha per 250 cy) = 0.033 ha per kcy
	NS	Scenario is not specific to SWLDR project but is drawn from dredge entrainment literature, which describes regression relationship between crab/ha and crab/kcy for particular types of dredges; the nonspecific scenario assumes crab are equally distributed throughout the project volume regardless of surface area:volume relationship)
	MCR	Mouth of the Columbia River: entrainment directly measured on dredge *Essayons* in July and August 2002 (Williams and Pearson 2005). Like the NS scenario, MCR assumes crab are equally distributed throughout the project volume, regardless of surface area:volume relationship.
Crab Population Density (T)	T rel	Relative trawl density: average trawl density from Sump Area 2 in July and August 2003
	T abs	Absolute trawl density: relative trawl density adjusted for trawl gear efficiency of 3.3% for YOY and 50% for all other age classes during summer sampling periods (from Stevens and Armstrong 1984).
Entrainment Function Coefficient (β)	1.0	100% of crab in (beam) trawl are entrained by dredge
	0.1	10% of crab in (beam) trawl are entrained by dredge
	0.27	Crab/kcy in hopper dredge = 0.27 crab/ha relative crab density in beam trawl
	0.09	Crab/kcy in pipeline dredge = 0.09 crab/ha relative crab density in beam trawl (pipeline dredge efficiency = 0.33 hopper dredge efficiency)
	1.75, 6.7	Dredge entrains 1.75 times as many YOY crab and 6.7 times as many Age 1+ and older crab as are caught in (otter) trawl
	0.33	Pipeline dredge entrains one third as many crab as hopper dredge (pipeline = 0.33 hopper dredge)
Dredge Mortality (M)	M	Dredge mortality varies by age: YOY 10%, Age 1+ 60%, Age 2+ and up 86% mortality due to dredge entrainment
	1.0	100% mortality of all entrained crab of all ages
Natural Survivorship (S)	S	Survivorship varies by age: YOY 1.7%, Age 1+ 16.0%, Age 2+ 64.9%, Age 3+ 45%
Fishery Harvest Rate	*H*	Probability of harvesting an adult male crab

Table 5. Input Variables, Levels of Variables for Each Input, Data Sources, and Assumptions for Each Model Step

Model Step	Input Variable	Levels	Data Source	Assumptions (by level)
1. Dredging Scenario	Volume	1	Corps of Engineers	500,000 cy from single pass over 17 ha sump area
	Season	1	Corps of Engineers	July through August
	Gear	1	Corps of Engineers	Cutter suction (pipeline) dredge (note that entrainment function may be specific to a different type of gear)
	dredge area: dredge volume	2	Corps of Engineers	SS scenario assumes project-specific area:volume relationship NS nonspecific scenarios assumes no area:volume relationship
2. Crab Population Parameters	Density	2	Williams et al. 2004	Average relative and absolute trawl densities in sump Area 2 during July-August
	Sex Ratio	1	Williams et al. 2003	Sex ratio assumed to be 1:1 for all ages and constant for July-August season
	Age / Size	1	Williams et al. 2003	Age/Size structure for sump Area 2 during July-August assumed to be constant for entire season
3. Entrainment Function	Crab Density/ Crab Entrainment Relationship	5	Armstrong et al. 1987, Larson et al. 1993, Pearson et al. 2002	Dredge entrains crab at one of five factors: a) 1.75 (Age 0+) and 6.73 (Age 1+), b) 1.0, c) 0.1, d) 0.27, and e) 0.09.
4. Dredged Volume	Volume in cubic yards	1	Corps of Engineers 2005	500,000 cy
5. Dredge Mortality	Instantaneous Dredge Mortality Rate	2	Armstrong et al. 1987, Crab Study Panel 1986	Dredge mortality is either 100%, or is age/size structured: 10% Age 0, 60% Age 1+, 86% >Age 1+
6. Natural Survivorship	Natural Survival Rate to Age Class of Interest	1	Armstrong et al. 1987, Wainwright et al. 1992	Assume same crab natural mortality rates by age class as in Grays Harbor
7. Loss of Recruits to Fishery	Harvest Rate of Male Crab	1	Armstrong et al. 1987, Wainwright et al. 1992	Assumes 70% of Age 3+ male crab will be harvested

Table 6. Summary of Modeled Scenarios, SWLDR Dredge Impact Model

Dredging Scenario	Crab Population (T) [a]	Entrainment Function Coefficient (β)	Dredge Mortality (M)
SS	T rel	1.0	M[b]
SS	T abs	1.0	M
SS	T rel	0.1	M
SS	T abs	0.1	M
NS	T rel	0.27	M
NS pipeline	T rel	0.09	M
NS	T abs	1.75, 6.7	M
SS	T rel	1.0	1.0
SS	T abs	1.0	1.0
SS	T rel	0.1	1.0
SS	T abs	0.1	1.0
NS	T rel	0.27	1.0
NS pipeline	T rel	0.09	1.0
NS	T abs	1.75, 6.7	1.0

a. T values are average crab/ha for July-August 2003 Area 2 trawls unless otherwise noted.
b. M = Age-related dredge mortality.

Table 7. Summary of Reference Scenarios for SWLDR Dredge Impact Model

Dredging Scenario	Crab Population (T) [a]	Entrainment Function Coefficient (β)	Dredge Mortality (M)
MCR 500 kcy	direct measure	1.0	M[b]
MCR 500 kcy, pipeline	direct measure	0.33	M
SS Ref	T rel UCL99[c]	1.0	1.0
SS Ref	T abs UCL99	1.0	1.0
NS SS Ref[d]	T abs	0.27	1.0
NS SS Ref, pipeline	T abs	0.09	1.0

a. T values are average crab/ha for July-August 2003 Area 2 trawls unless otherwise noted.
b. M = Age-related dredge mortality.
c. UCL99 = 99% upper confidence limit.
d. NS SS Ref is a hybrid scenario in which the dredged volume is adjusted to account for the assumption that the sump will be dredged in a single pass, and that crab are likely to be distributed only in the upper 2 ft of material over the sump area, or approximately 135 kcy.

Table 8. Dungeness Crab Entrainment and Loss Estimates for SWLDR Modeled Scenarios

Modeled Scenario[a]					Total Entrainment		Adult Equivalent Loss to Age 2+		Adult Equivalent Loss to Age 3+		Loss of Recruits to Fishery	
Dredging Scenario	Entrain-ment Function Coefficient (β)	Crab Population (T)[b]	Dredge Mortality (M)	Entrainment Rate R, crab/cy	E, number crab	SE[c]	AEL 2+, number crab	SE	AEL 3+, number crab	SE	LRTF, number crab	SE
SS	1.0	T rel	M[d]	0.007	3282	3943	1257	806	566	363	198	127
SS	1.0	T abs	M	0.024	11758	11251	2522	1612	1135	726	397	254
SS	0.1	T rel	M	0.001	328	394	126	81	57	36	20	13
SS	0.1	T abs	M	0.002	1176	1125	252	161	114	73	40	25
NS	0.27	T rel	M	0.054	26849	32257	10284	6596	4628	2968	1620	1039
NS pipeline	0.09	T rel	M	0.018	8950	10752	3428	2199	1543	989	540	346
NS	1.75, 6.7	T abs	M	0.103	51432	54786	16930	10851	7619	4883	2667	1709
SS	1.0	T rel	1.0	0.007	3282	3943	1539	1032	692	464	242	163
SS	1.0	T abs	1.0	0.024	11758	11251	3163	2068	1423	931	496	326
SS	0.1	T rel	1.0	0.001	328	394	154	103	69	46	24	16
SS	0.1	T abs	1.0	0.002	1176	1125	316	207	142	93	50	33
NS	0.27	T rel	1.0	0.054	26849	32257	12588	8443	5665	3799	1983	1330
NS pipeline	0.09	T rel	1.0	0.018	8950	10752	4196	2814	1888	1266	661	443
NS	1.75, 6.7	T abs	1.0	0.103	51432	54786	20829	13892	9373	6251	3281	2188

a. Scenarios and inputs are defined in Table 5. T values are average crab/ha for July-August 2003 Area 2 trawls unless otherwise noted.
b. T values are average crab/ha for July-August 2003 Area 2 trawls unless otherwise noted.
c. SE standard error.
d. M = age-related dredge mortality.

Table 9. Dungeness Crab Entrainment and Loss Estimates for Reference Scenarios

Reference Scenarios				Entrainment Rate R, crab/cy	Total Entrainment		Adult Equivalent Loss to Age 2+		Adult Equivalent Loss to Age 3+		Loss of Recruits to Fishery	
Dredging Scenario	**Entrainment Function (β)**	**Crab Population (T) [a]**	**Dredge Mortality (M)**		**E, number crab**	**SE[b]**	**AEL 2+, number crab**	**SE**	**AEL 3+, number crab**	**SE**	**LRTF, number crab**	**SE**
MCR entrainment study direct measurements, July-August 2002												
MCR 500 kcy	1	NA (direct)	M[c]	0.061	30713	4973	18619	3431	8378	1544	1095	192
MCR 500 kcy, pipeline	0.33	NA (direct)	M	0.061	10135	1641	6144	1132	2765	510	361	64
SS Dredging Scenario using T = upper 99% Confidence Limit of Sump Area 2 Trawls												
SS Ref	1	T abs UCL99[d]	1.0	0.044	22225	11252	5234	2068	2355	931	824	326
SS Ref	1	T rel UCL99	1.0	0.013	6353	3943	2540	1032	1143	464	400	163
"Hybrid" nonspecific dredging scenarios adjusted for single pass dredging event of proposed sump												
NS SS Ref	0.27	T abs	1.0	0.192	25975	24856	6987	4564	3144	2056	**1100**	720
NS SS Ref, pipeline	0.09	T abs	1.0	0.064	8658	8285	2329	1523	1048	685	**367**	240

a. T values are average crab/ha for July-August 2003 Area 2 trawls unless otherwise noted.
b. SE Standard error.
c. M = age-related dredge mortality.
d. UCL99 = 99% upper confidence limit.

Table 10. Summary of Dungeness Crab Entrainment and Loss Estimates for SWLDR Modeled and Reference Scenarios

Dredging or Reference Scenario[a]	Entrainment Function Coefficient (β)	Crab Population (T)[b]	Dredge Mortality (M)	Entrainment Estimates		Loss Estimates (number crab)		
				R, crab/cy	E, number crab	AEL 2+	AEL 3+	LRTF
NS	1.75, 6.7	T abs	1	0.103	51432	20829	9373	3281
NS	1.75, 6.7	T abs	M[c]	0.103	51432	16930	7619	2667
NS	0.27	T rel	1	0.054	26849	12588	5665	1983
NS	0.27	T rel	M	0.054	26849	10284	4628	1620
NS SS Ref	0.27	T abs	1	0.192	25975	6987	3144	1100
MCR, 500 kcy	1	NA (direct)	M	0.061	30713	18619	8378	1095
SS Ref	1	T abs, UCL99[d]	1	0.044	22225	5234	2355	824
NS pipeline	0.09	T rel	1	0.018	8950	4196	1888	661
NS pipeline	0.09	T rel	M	0.018	8950	3428	1543	540
SS	1	T abs	1	0.024	11758	3163	1423	496
SS Ref	1	T rel, UCL99	1	0.013	6353	2540	1143	400
SS	1	T abs	M	0.024	11758	2522	1135	397
NS SS Ref, pipeline	0.09	T abs	1	0.064	8658	2329	1048	367
MCR, 500 kcy, pipeline	0.33	NA (direct)	M	0.061	10135	6144	2765	361
SS	1	T rel	1	0.007	3282	1539	692	242
SS	1	T rel	M	0.007	3282	1257	566	198
SS	0.1	T abs	1	0.002	1176	316	142	50
SS	0.1	T abs	M	0.002	1176	252	114	40
SS	0.1	T rel	1	0.001	328	154	69	24
SS	0.1	T rel	M	0.001	328	126	57	20

a. Reference scenarios are shaded.
b. T values are average crab/ha for July-August 2003 Area 2 trawls unless otherwise noted.
c. M = age-related dredge mortality.
d. UCL99 = 99% upper confidence

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